Surface Water Quality Modeling for Pollution Assessment and TMDL Development

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SUMMARY: Under the provisions of the Clean Water Act (CWA), water quality modeling plays a central role in development of control strategies for both point and nonpoint pollutants. These pollutants include oxygen demanding substances, toxic chemicals, whole effluent toxicity, nutrients, and pathogens or surrogate organisms. The CWA broadly defines procedures for the determination of the "Total Maximum Daily Load" (TMDL) of pollutants and the allocation of the load between the various natural, nonpoint, and point sources. Federal guidance and Louisiana policies further specify procedures to be followed.

Water quality models are utilized in the assessment of pollutant sources, pollutant transport, and environmental transformation, as well as in the determination of appropriate load limitations and management practices. Many water bodies in Louisiana have been modeled for these purposes, including, for example, the Calcasieu Estuary, the Vermilion River, Bayou Grand Caillou, Bayou Plaquemine Brule at Crowley, and Big Creek in the Tangipahoa Basin.

Model selection depends on a variety of factors. At times, steady state models are adequate for the purpose of TMDL development, however, in more complex environments, such as estuaries, a dynamic model is often required. Special studies are generally required to collect the data necessary for calibration of these models. Studies performed in support of development of these water quality models are termed intensive, or synoptic, surveys. Under estuarine conditions, certain aspects of the design of these studies must be modified, and often may gain additional significance. Use of a tracer dye can, for example, facilitate the assessment of estuarine transport and pollutant transformation. Use of satellite global positioning systems (GPS) also has been found to provide a needed utility. For model development, the utilization of a geographic information system (GIS) for site mapping, database support, and spatial definition and segmentation has provided increased efficiency and flexibility.

Efforts to develop water quality models, TMDLs, and wasteload allocations for Louisiana waters continues. These efforts will not only assist Louisiana in point and nonpoint source pollutant management, but will also provide a basis for better understanding the special characteristics of Louisiana's water resources.

INTRODUCTION

The Louisiana Department of Environmental Quality (LDEQ) has responsibility for the development of the Louisiana Water Quality Standards, and the development of a Water Quality Management Plan which provides for the attainment of these standards in Louisiana's surface

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waters. Several Louisiana universities have provided technical assistance to the LDEQ in support of the development of this plan. Among these, the University of Southwestern Louisiana's (USL) Center for Louisiana Inland Water Studies (CLIWS) has provided a part of the technical assistance, especially in the area of water quality modeling. This paper summarizes the water quality modeling procedures required for TMDL development.

POLLUTANT MODELING AND LOAD ALLOCATION

The CWA and resulting regulations which implemented the provisions of the CWA, place specific requirements on state and federal regulators (Mackey and Gladden 1985; USEPA 1985). The State of Louisiana and Region VI of the USEPA have been collaborating for several years to develop technical procedures needed for implementing water quality models and TMDL development. These regulations and procedures are based on several definitions:

A **load** is the amount of matter or thermal energy that is introduced into a receiving water. A load may be caused by man (a pollutant load) or by nature (a natural background load). For oxygen demanding material, load may be expressed separately for separate components (e.g. CBOD, NH_3-N), or may be expressed as a total oxygen demand. **Numerical criteria** for maximum and/or minimum water quality parameters have been defined by the LDEQ through the publication of **Water Quality Standards**. The **load capacity** of a stream is the greatest amount of loading that a water can receive without violating these criteria. If seasonality and flow are not considered in the determination of the load capacity, annual **critical conditions** are used as a basis. Load capacity may also be determined on a seasonal or flow and temperature variable basis.

The **load allocation** (LA) is the portion of a receiving water's load capacity that is attributed either to one of its existing or future nonpoint sources of pollution or to natural background sources. Load allocations are best estimates of the loading which may range from reasonably accurate estimates to gross allotments, depending on availability of data and appropriate techniques for predicting the loading. Wherever possible, natural and nonpoint source loads should be separately estimated. For calibrated modeling studies, the LA may often be estimated from the headwater flow, incremental flow loads, and nonpoint loads required for calibration.

A **wasteload allocation** (WLA) is the portion of a receiving stream's loading capacity that is allocated to one of its existing or future point sources of pollution. The WLA constitutes a type of water quality based effluent limitation. Under Louisiana policy, every waterbody for which one or more WLAs are developed also has a designated WLA for future growth and safety (Figure 1 from Waldon 1991). Typically, the LDEQ reserves twenty percent (20%) of the allocable TMDL (see below) for this WLA. This allocation for growth and safety is also referred to in EPA guidance as a margin of safety (MOS).

The **total maximum daily load** (TMDL) establishes the allowable loadings or other quantifiable parameters for a waterbody, and thereby provides the basis for water-quality based controls. The TMDL for a substance is the sum of the individual WLAs for point sources, safety, and reserve, and the LAs for nonpoint sources and for natural background. The allocable TMDL is the loading capacity minus the LAs for a waterbody.

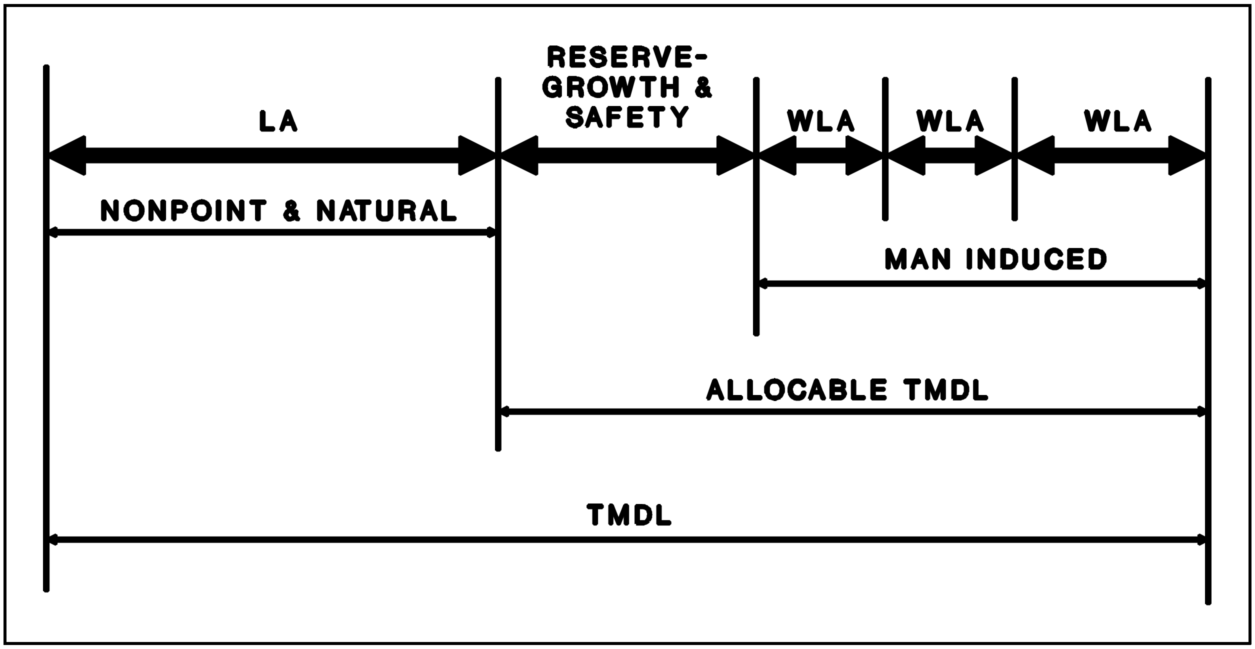

Figure 1. Components of Total Maximum Daily Load.

Nonpoint source tradeoffs are provided for in the allocation process. If **best management practices** (BMPs) or other nonpoint source pollution controls make more stringent LAs practicable, then wasteload allocations can be less stringent.

Allocation of loads between the various point source dischargers is a difficult management decision. Within the constraints of the TMDL requirements, the selection of allocation methodology to be applied is a responsibility of the State.

Various load allocation schemes have been proposed, and each may be most appropriate in particular circumstances (Burn and Barbara L 1992). A wasteload allocation strategy should

- be protective of the environment and reduce the risk of exceedance of water quality standards,
- be equitable to all regulated parties,
- provide a reasonable distribution of costs of load reductions, and attempt to minimize overall costs of meeting TMDL requirements.

If all dischargers are of similar size, it will usually be most equitable to set equal concentration limits for each discharger. Where both small and large dischargers are involved, the Louisiana "Statewide Sanitary Effluent Limitations Policy" (LDEQ not dated) may be followed, so far as possible, in setting limitations on smaller sanitary dischargers.

If dischargers are not similar, for example, if industries and municipalities are involved, it may be more appropriate to require an equal percent removal, or equal reductions from technology based limits (e.g. secondary or BAT guidelines), rather than simply requiring equal concentration limits. Note, however, that for some industries such as food processors, LDEQ has determined that the character of the waste and waste treatment methods are sufficiently similar to sanitary waste to be included in an overall allocation without consideration of wastewater source or specific industry category.

If multiple dischargers are owned by a single entity, a city for example, it may be appropriate to consult with the permittee to determine the most cost-effective allocation. If such an allocation strategy is pursued, contact with the regulated municipalities or industries should be initiated as early as practical during the TMDL development process. Both point and nonpoint pollution have significant impacts on water quality in most basins. Nonpoint sources of pollution include urban runoff and agricultural runoff. Point sources include municipal treatment plants, small sanitary treatment "package" plants, commercial and recreational vessel discharges, oil and gas related discharges, seafood processors, and other industrial discharges. While point sources are likely to have substantial impact in the vicinity of the point source discharge locations, total pollutant loads from nonpoint sources are likely to account for the larger part of the total pollutant load to the basin. Significant loads of organic materials and coliform bacteria also likely originate from natural sources.

In cases involving nonpoint sources, the tradeoff between point and nonpoint load must be considered. Because of the uncertainty which is usually associated with nonpoint source loading estimation and BMP reductions, a **phased TMDL** is likely to be required when such trades are proposed. When developed according to a phased approach, the phased TMDL can be used to establish load reductions where there is impairment due to nonpoint sources or where there is lack of data or adequate modeling. Lack of information about certain types of pollution problems (for example those associated with nonpoint sources or with certain toxic pollutants) may not be used as a reason for delay of implementation of water quality-based controls (USEPA 1991a).

The phased TMDL will normally include a monitoring plan. This plan should include a description and assessment of existing data and the design of additional monitoring or special studies which will be required. The objectives of the monitoring plan should include:

- Assessment of water quality standards attainment,
- Verification of pollutant source allocations,
- Model calibration or modification,
- Measurement of stream discharge, dilution, and development of mass balances,
- Evaluation of effectiveness of point and nonpoint source controls.

The monitoring plan must include a provision for appropriate QA/QC. Data from discharge monitoring reports (DMRs) and data collected by other agencies and organizations should also be considered. A proposed schedule for data collection and evaluation must also be included in the plan. A proposed phased TMDLs has been developed for Bayou Plaquemine-Brule at Crowley (Waldon 1990; Waldon 1996).

TMDLs and WLAs for **toxic substances** and **toxicity** (USEPA 1991b) may be developed using one or more of three technical approaches:

- Chemical specific,
- Whole effluent toxicity, and
- Biocriteria/bioassessment.

In each situation, selection of the approach for protecting receiving water quality is dependent on the specific environmental conditions and regulatory resources available. The chemical specific approach is likely to be most commonly applied. Whole effluent toxicity has become a common test used in NPDES permitting, and is therefore likely to be more commonly utilized in toxic TMDLs. Application of the biocriteria/bioassessment approach is more difficult and currently less practical because methodologies are not fully developed and resources are not as readily available.

Special attention is required to assure that discharges of persistent and/or highly bioaccumulative toxic pollutants do not result in a loss of use or standards exceedance. The numerical criteria for these substances have been selected to be protective of water quality for typical point source discharges. Additional analysis and modeling may be required in cases of diffuse sources or multiple discharges to a waterbody.

Although chemical contaminant based loads and load reductions form the major thrust of all past, as well as most future, TMDLs, in some situations water quality standards can only be attained if non-chemical factors such as hydrology, channel morphology, and habitat are addressed. In such cases it is appropriate to use the TMDL process to establish control measures for quantifiable non-chemical parameters that are preventing the attainment of water quality standards. Control measures in this case would be developed and implemented to meet a TMDL that addresses these parameters in a manner similar to chemical loads (USEPA 1991a). The phased TMDL approach may be particularly appropriate for development of non-chemical factor TMDL requirements.

MODEL SELECTION

Model selection must be primarily based on the project goals and objectives, and on the constraints of the user. As an aid to model selection, models can be categorized according to various characteristics. Four important categories (USEPA 1991a) which should be considered in model selection are:

- Temporal characteristics
- Spatial characteristics
- Specific constituents and processes simulated
- Transport processes.

The selection of a water quality model depends on a number of factors. A model should be selected based on its adequacy for the intended use, for the specific waterbody hydrology and dischargers, and for the critical conditions applied to that waterbody. Typical TMDL/WLA studies which primarily consider point sources impacts in non-tidal streams may require little justification for model selection. However, in estuarine situations more extensive justification of model selection based on study site characteristics, model characteristics, and study objectives is required.

In general, the least sophisticated model capable of addressing all relevant receiving stream characteristics should be selected. Less sophisticated models usually require fewer resources and less data, and in some cases, may produce more robust and defensible results. When available and appropriate, models supported by the USEPA Center for Exposure Assessment Modeling (CEAM) may be preferred over other models of similar applicability. Models which have been applied in Louisiana for surface water quality modeling include:

! QUAL2E	This model evolved from older versions of the U.S. EPA QUAL and QUAL-II models (Brown and Barnwell 1987). QUAL2E is distributed in an executable form, as well as in FORTRAN source code. QUAL2E is a steady state one dimensional model which allows for complex branching. The QUAL2E input is relatively complex, and is not easily modified. QUAL2E is part of the EPA BASINS (Lahlou et al. 1996) modeling framework.
! WASP	This is a dynamic node and channel model (Ambrose et al. 1993). WASP is capable of simulating stratification, sedimentation and sediment processes, and complex flows. Although the user may develop or customize the dynamic subroutine (WASPB), two versions are distributed and supported. EUTRO is suitable for simulating complex transport and transformation of oxygen demanding substances, nutrients, algae, and pathogenic bacteria. TOXI is suitable for modeling the transport and transformation of toxic pollutants. WASP is also distributed with a compatible hydrodynamic simulation program, DYNHYD. WASP has been widely applied (Ambrose 1987; James et al. 1997; Pickett 1997), and is currently being applied by the author in collaboration with researchers at UNO to modeling Lake Pontchartrain, and in collaboration with Dr. Ehab Meselhe at USL modeling the Calcasieu Estuary.
! CORMIX	This family of models is suitable for modeling the near-field zone of initial dilution (ZID) and mixing zone (MZ) dilution for point source dischargers. CORMIX is capable of simulating both positively and negatively buoyant discharge plumes, and may be applicable to the analysis of some oilfield discharges. This model could be useful in TMDL analyses for toxic substances. CORMIX was developed at Cornell University and is supported through CEAM.
! BLTM	The Branched Lagrangian Transport Model is a branched one-dimensional stream model developed by the USGS (Jobson and Schoellhamer 1987; Schoellhamer 1988a; USGS 1998). BLTM incorporates QUAL2E water quality kinetics, and has also been widely tested and applied (Jobson 1980;

Jobson 1985; Jobson 1987a; Jobson 1987b; Schoellhamer 1988b). BLTM is based on a Lagrangian transport concept which routes parcels of water through the branched stream system. This model has been used in Louisiana for TMDL modeling in tidal or reversing flow streams (Waldon 1997; Waldon 1998; Waldon et al. 1999).

Use of a limited number of models greatly increases the efficiency of model application and review. However, the models listed above may not be adequate or appropriate in many situations. Selection of additional models will depend on the system to be simulated and on computer hardware and software availability. However, in order to facilitate public and professional review, as well as future applications and extensions, public domain models with extensive documentation and support should be given preference in model selection for management planning applications.

MODEL IMPLEMENTATION

Traditionally, water quality modeling for pollution management and TMDL development uses a defined **critical condition**. The critical condition definition can have a significant influence on model selection. Critical conditions are also referred to in EPA guidance as **design conditions**, but are generally referred to here as critical conditions to avoid confusion with treatment facility design flows. Critical conditions are the reasonable "worst case" conditions for the waterbody. The State Water Quality Standards and technical procedures provide definitions which are typically used for modeling environmental impacts under critical conditions. Often, point sources with continuous discharges present the greatest impact on the waterbody during low-flow (drought), and high-temperature conditions. Under some conditions, such as flow related discharges or waterbodies heavily impacted by nonpoint source pollutants, more appropriate critical conditions may be technically justified.

There are several types of water bodies for which dissolved oxygen water quality models are not generally reliable predictive tools. Swamps, wetlands, and some lakes fall into this category. For these waterbodies alternative methods for determining TMDLs and WLAs may be required.

Dissolved oxygen, nutrient enrichment and eutrophication of lakes present particular difficulties in model analysis. Except in rare circumstances, large computerized, ecological models of lakes are not recommended for nutrient TMDLs. Large data requirements, lack of scientific consensus, as well as professional resource requirements make these models impractical for most applications.

From the standpoint of dissolved oxygen, if there are data which show that under current conditions water quality standards are being met and there are no nuisance problems associated with present discharges, then current effluent limitations and management practices should be adequate. For some impoundments standard stream models may provide an adequate and appropriate management model. In this case dispersion and photosynthesis should be taken into account.

For lake or estuary nutrient loading, nutrient budget models (Mancini et al. 1983; Waldon and Bryan 1998) may be used to determine if nutrient reductions should be considered, and the degree of reduction required. If nutrient loading is determined to be a problem, reduction of point source loading should be considered. The relative magnitude of nonpoint sources and their abatement possibilities should also be considered. Relocation of discharges or diffusers may be recommended to eliminate some localized or nuisance problems in lakes.

Swamps and wetlands present another situation in which presently available, complex computer models may not be appropriate for water quality management decisions. In some situations uses may be enhanced through such discharges, while in other cases, uses may be degraded or completely lost because of wastewater or nonpoint pollutant discharges to these water bodies. For current dischargers to swamps, wetlands, etc. the current impact can be evaluated in terms of its impact on uses, and the physical, chemical, and biological impact. A comparison should be made between upstream and downstream sites. For those waterbodies not sufficiently defined by a channel, sites near the discharge may be compared to control or reference sites which are not as heavily impacted. Where the discharger is having a detrimental impact in terms of water quality standards and/or reduced quality and diversity of species, reduced effluent limitations should be imposed, or an alternative treatment system and effluent discharge system may be considered. Swamps and wetlands may be able to receive and assimilate the wastewater with proper diffusion of the effluent.

If upstream or control site data for swamps and wetlands show contravention of standards then the standards should also be reviewed. To prevent delays, the TMDL/WLA should concurrently be developed, and if necessary, the phased TMDL procedures applied. Comparisons to existing discharges can be utilized to estimate the impact of a proposed discharge.

Modeling of bacterial contamination and development of model-based bacterial management strategies is not as well understood as modeling and management of oxygen demanding pollutants. At present it is simply assumed that bacterial limitations or disinfection are necessary to protect human health uses for all significant sanitary dischargers. Future experience, modeling developments, and EPA guidance may demonstrate the needs for additional routine controls, BMPs, and TMDL procedures.

MODEL CALIBRATION - DATA NEEDS

Water quality modeling is central to the development of water quality management plans, TMDLs, and WLAs. Data requirements for model development are dependent on various specific environmental and pollutant loading conditions, on the level of model accuracy, and uncertainty or credibility required as a basis for management decision making. In all cases the primary consideration which should be given in defining data requirements is that the resultant model must provide a reasonable scientific basis and allow for a confident and defensible water quality decision.

Four levels of water quality analysis may be defined: (1) mass balance and dilution analysis, (2) uncalibrated modeling, (3) calibrated modeling, and (4) calibrated and verified modeling. These four levels of model analysis are listed in order of increasing data requirements.

A simple **mass balance (or budget) and dilution analysis** may, in some situations, adequately support management decisions. Extremely conservative assumptions may be applied to provide estimates of limits of pollutant or other levels which might result under specific management scenarios. In this case very limited data may be adequate for supporting management decisions.

Uncalibrated models use more realistic transport and transformation relationships, but are based on little or no site specific data. Uncalibrated model inputs should typically be based upon field observations of stream width, depth, and velocity at or near low flow conditions. However, no water quality data are required and model kinetics are estimated.

Calibrated models analyses are developed using model hydraulic and kinetic rates which are estimated from data collected during one or more field studies. A model is said to be calibrated if these hydraulic and kinetic rates cause the model to adequately reproduce the data. Development of a calibrated model requires extensive measurement of water quality, stream geometry and hydrology on one occasion. Procedures for performing such a study (intensive water quality survey) may be found in the LDEQ QA/QC document and EPA guidance (LDEQ 1991; Mackey and Gladden 1985).

Calibrated and verified models utilize data from two separate water quality surveys. One survey is used to calibrate the model as described in above. The calibrated model is adjusted to account for changes in stream loads and temperature during the second survey and is then used to predict water quality observations during the second survey. Any additional model parameters which are altered during verification from their calibration settings must be documented and a detailed rationale provided for the appropriateness of such a variation. The model is considered verified when it adequately reproduces this second set of water quality data. Verified models provide a higher level of credibility for other model projections made in support of management and planning.

SPECIAL ASPECTS OF LOUISIANA WATER BODIES

There are many special aspects which need to be considered in development of research and management planning in Louisiana. These special considerations arise from the unusual hydrological conditions, logistical requirements, and ecological complexities which are present. Low velocities and highly transient flow conditions often make estimation of flow more difficult. In many coastal Louisiana streams traditional current velocity meters have been found to have very limited value in projecting net advective water movement. Dye tracers have been satisfactorily utilized to measure water movements in low-velocity water bodies (Everett 1991). The use of dye tracers not only can provide an integrated determination of water movement, but also provides a basis for estimating dispersion (Smart and Laidlaw 1977). An understanding of these processes is a fundamental part of any water quality modeling effort. Such modeling can also support contaminant spill tracking, projection, and investigation.

Low velocities and transient flows also profoundly affect the design of water quality intensive surveys which support water quality model development. One classification of these intensive surveys is based on the method of sampling site selection. Surveys termed as Eulerian studies sample fixed locations at predetermined times. Alternatively, in surveys termed

Lagrangian studies sampling is based on observed or calculated water movement. Typically, in a Lagrangian survey, a dye tracer is used to "tag" a volume of water. Samples are then taken at the location of the dye peak at preselected time intervals. Lagrangian water quality studies appear to be the most appropriate design for slowly flowing Louisiana streams.

Reaeration rate and volatilization rates for organic contaminants are another class of processes which are less well understood in slow moving and tidal waterbodies. In moving streams empirical formulas are available which provide estimates of these rates. Relatively little research into these processes has been done in slow moving and tidal streams. The estimation of the reaeration rate in a water body is critical in development of dissolved oxygen concentration (DO) models, as well as modeling volatile contaminants. Although numerous studies have been performed measuring reaeration rate, relatively few of these studies have been performed in tidal or very slow moving streams. Indeed, Bowie, *et al*. (1985) state that there has been a "lack of estuarine reaeration research." This lack of research is particularly important because pollution problems are often most extreme near the mouths of streams and rivers. Tidal streams and estuaries provide recreation, transportation, and a habitat for aquatic biota, and naturally attract urban and industrial development.

Propane studies for reaeration measurement are a significant advance over indirect methods, and empirical formulas (Downer and Edward R. Holley 1991; Kilpatrick et al. 1987; Rathbun et al. 1975; Thene and Gulliver 1990). Propane methods typically follow an approach in which the tracer and dye are injected into a flowing stream, and the respective peaks measured at sites downstream. Gulf Coast streams are often influenced by low energy tides, and some have been termed "stretch lakes" due to their sluggish, depositional environments. Measurement of reaeration in these environments by the traditional tracer methods is impractical because there is little or no net water movement (Waldon et al. 1991).

Steps in TMDL model development:

- Determine watershed area to be modeled and streams to be included
- Inventory dischargers and nonpoint sources, contact interested parties
- Identify pollutants of concern, relevant water quality standards, and critical conditions
- Estimate geometry - stream lengths, widths, areas of ponds and lakes
- Select appropriate model
- Perform initial modeling
- Determine data needs, design and perform field studies to provide needed data
- Develop calibrated model
- If required, collect additional data and develop verified model
- Determine TMDLs by successively running model until standards are just met
- Allocate loads among point sources, nonpoint sources, natural sources, and MOS
- Seek approval of state and EPA, update state water quality management plan

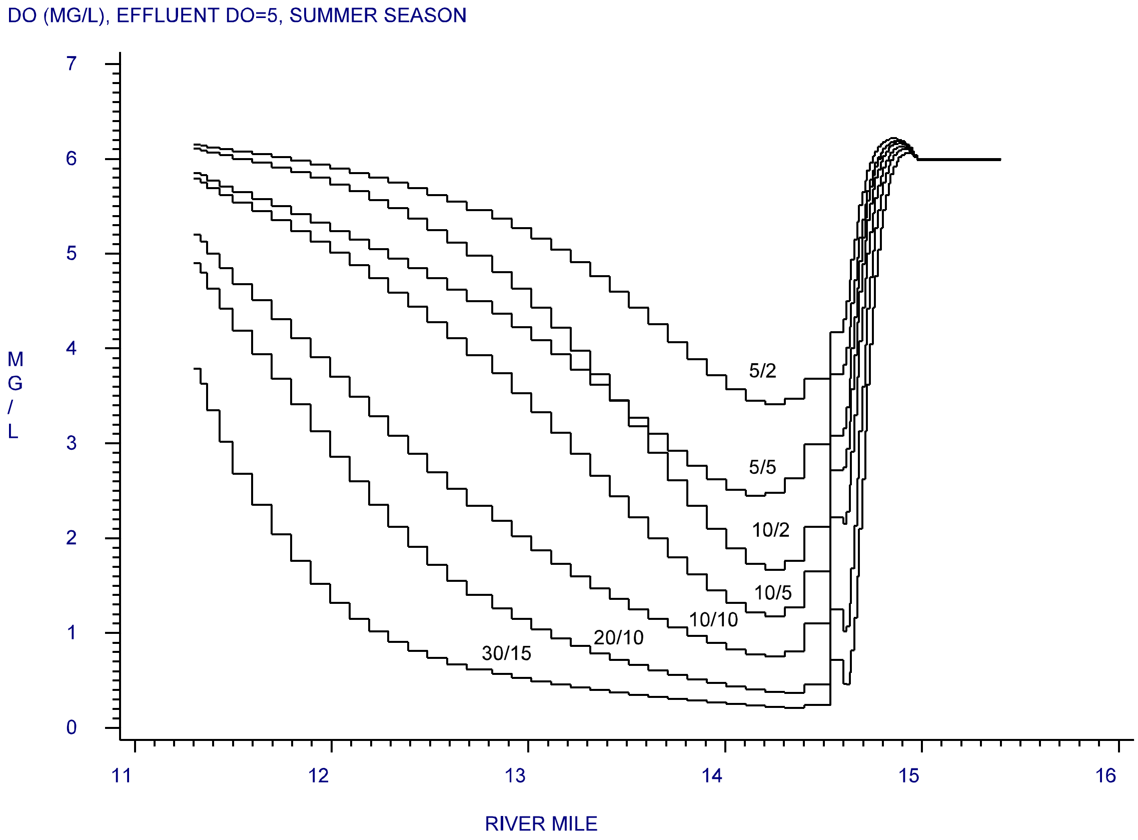

Figure 2. Projected critical summer season DO with 5 mg/L effluent DO, Bayou Plaquemine-Brule at Crowley (Waldon 1996).

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[2] Reports numbered as WQR (Water Quality Reports) and WLA (Wasteload Allocation Reports) were developed by personnel of the CLIWS, and funded through interagency agreements with the LDEQ. As such, these reports do not necessarily represent the opinions or policies of the LDEQ.

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